# Assessment of Timing and Performance based on Trajectories from low-cost GPS/INS Positioning

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**KEY WORDS**

GPS positioning and timing, INS, Chronometry, Trajectory analysis

## INTRODUCTION

Traditionally, development and testing of materials or equipment has been based on repeated measurements with resources including timing cells or wind tunnels. Similarly, the analysis of athletes' performance often relies on techniques such as measuring race segments (chronometry) or video recordings. These methods however, either appear vulnerable to meteorological conditions (e.g. video), present the difficulty of replicating the posture and movements of test subjects from one trial to the next or have a discrete character (e.g. timing). On the other hand, researchers, coaches and athletes are interested in observing certain phenomena continuously and under all conditions. Satellite-based positioning offers continuous observation of the athletes' trajectory (timing, position, velocity). When coupled with inertial navigation systems (INS), it further allows observing accelerations and orientations. Not until recently, the cost, processing complexity and bulkiness of the GPS/INS technology often discouraged its regular employment (Figure 1). (Waegli and Skaloud 2007) have introduced an economic and ergonomic GPS/INS system based on differential L1 GPS receivers and Micro-Electro-Mechanical System (MEMS) inertial measurement units (IMU). In this paper, we first assess the accuracy of such low-cost system by comparison to a more precise reference. Then, we use its output to derive the ski's edging and skidding angles to illustrate the new possibilities in the application of this technology. Finally, we derive timing information and compare its performance to the chronometry provided by timing cells.

## METHODS

MEMS-IMUs are subject to large random and systematic errors (biases, scale factors, misalignment, and noise) which need to be suppressed in order to provide useful information on orientation and displacement. For instance, typical uncalibrated biases of a MEMS accelerometer reach 0.5m/s$^2$ which deviates the position by 50m in 10s. A solution for calibrating these errors consists in the integration of MEMS-IMU with satellite positioning where the GPS antenna is tightly attached to the inertial sensors. However, the conventional GPS/INS integration strategies (Titterton and Weston 1997) need to be adapted due to the error characteristics of the MEMS-IMU sensors (Waegli, Skaloud et al. 2007).

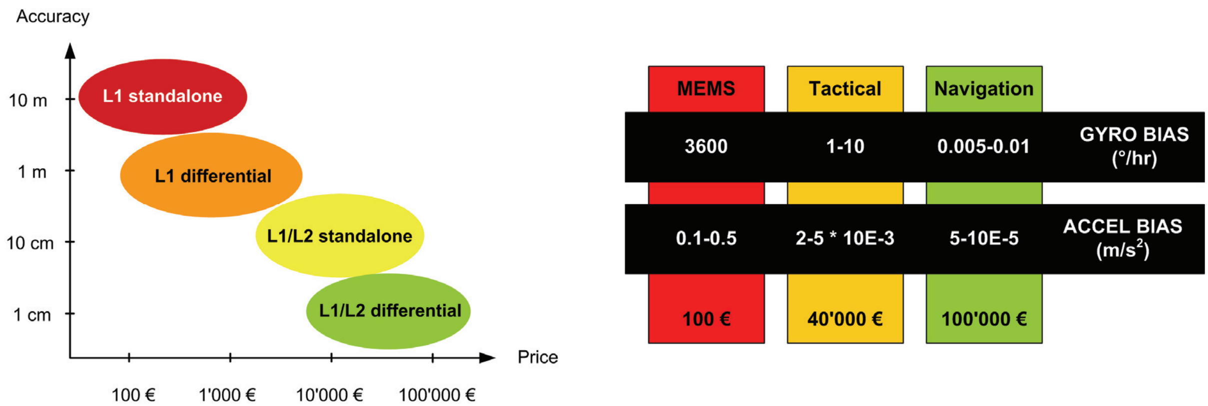


**Figure 1: Accuracy versus prizing of current GPS (differential) methods and IMU hardware.**

To evaluate the position, velocity and orientation accuracy of the low-cost system, this one was mounted on an athlete together with a reference provided by dual-frequency GPS receivers and a tactical-grade IMU. The differential L1 GPS solution at 1Hz was integrated with the triple-axis accelerometer and gyroscope measurements of the MEMS-IMU provided at 100Hz. The reference system (Skaloud, Vallet et al. 2006) yields cm accuracy for position, cm/s for velocity and 1/100° for orientation (Figure 2).

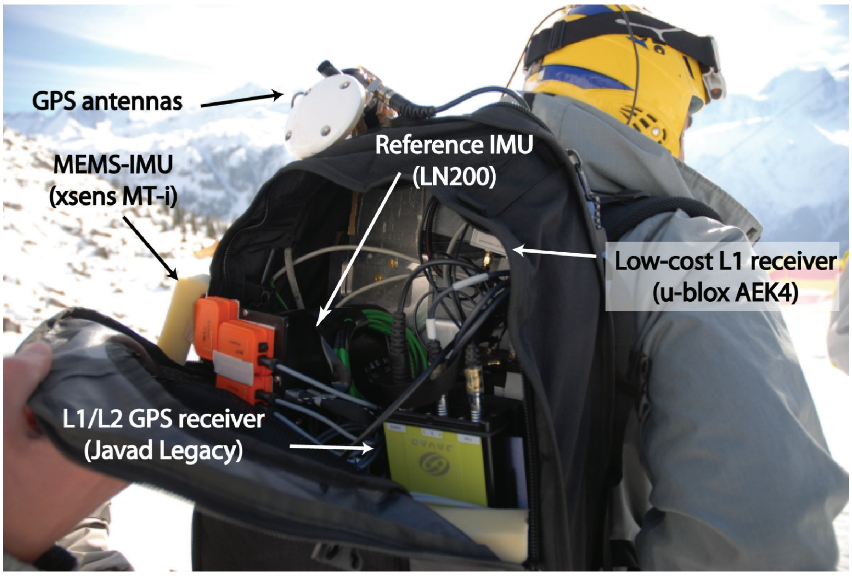


**Figure 2: Low-cost and reference GPS and IMU mounted on a skier. In order to compare the systems accurately, all the sensors had to be installed on the same, rigid platform.**

The comparison of 6 runs of a giant slalom showed that the GPS/MEMS-IMU system offers mean accuracies (1σ) better than 0.4m for position, 0.2m/s for velocity and 1-2° for the orientation. The accuracy indicators can be used to show clearly when the observed phenomenon is statistically significant as illustrated in figure 3 (dotted around the trajectory). Simulations outages in GPS data unveiled that these can be bridged by inertial navigation up to 10s while maintaining accuracy (Waegli and Skaloud 2007).

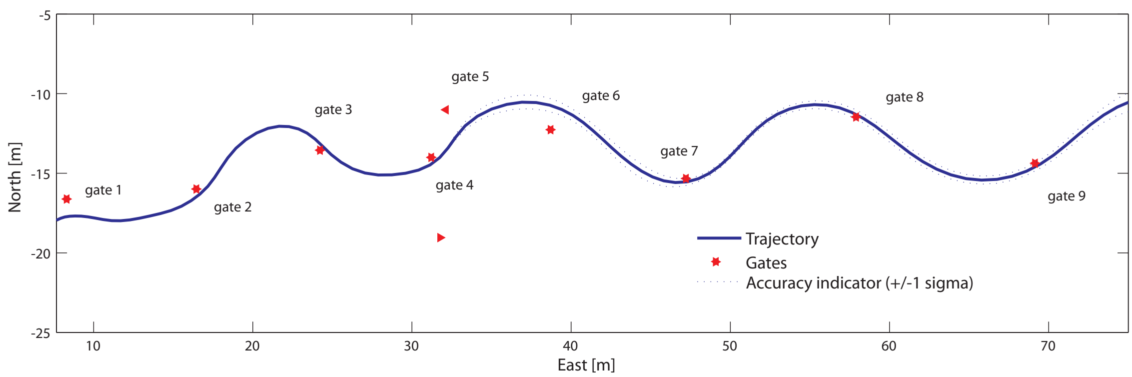


**Figure 3: GPS/MEMS-IMU trajectory with accuracy indicator (1σ). Satellite masking decreased the positioning accuracy around gate 6 but the INS helped to bridge the GPS gaps efficiently.**

## RESULTS

### Ski Orientation Determination

In alpine skiing, the determination of accurate orientations of a ski is the prerequisite for analyzing forces acting on the ski. Forces need to be decomposed with respect to the terrain in order to analyze potential and kinetic energies, as well as joint loading and energy transfers during a turn. Nowadays, the ski's orientation can be obtained from multi cameras system with a precision of 5 degrees for an object orientation (Richards 1999). However, this method requires an important infrastructure and is not adapted for every-day use and training purposes. Skis equipped with GPS/MEMS-IMU provide a new method which is more accurate, faster, easier to setup and insensitive to the weather conditions. For a complete investigation, both skis need to be equipped with GPS and MEMS-IMU sensors to recover the position and orientation of both skis.

Based on the slope information derived from a digital terrain model and the trajectory derived from the GPS/MEMS-IMU integration, the orientation of the ski with respect to the slope can be computed. The local referential ($x,y,z_{slope}$) is defined as follows (Figure 4): the xy plane represents the local surface with the x-axis aligned to the maximum slope of the terrain (fall line). The heading is the angle between the direction of the maximum slope ($x_{slope}$) and the direction of the ski ($x_{ski}$). The roll describes the edging angle of the ski.

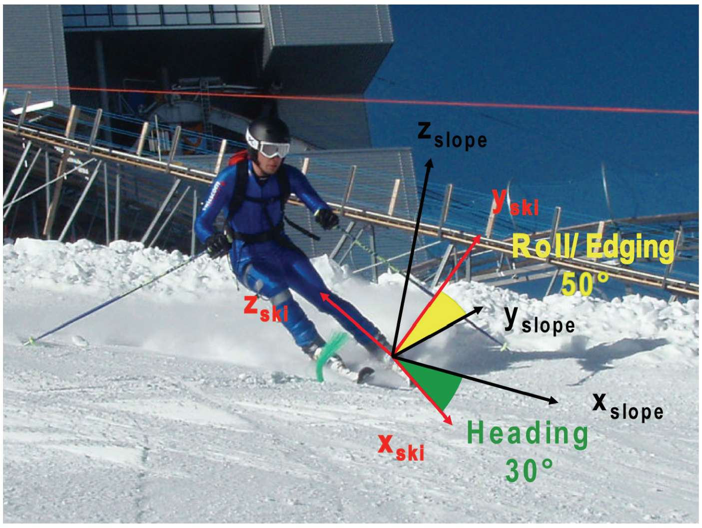


**Figure 4: Left figure: Definition of the reference frames and illustration of the heading and roll (edging) angles. Right figure: Definition of the skidding angle.**

The zoom on the two turns illustrated in figure 5 allows studying the technique of the athlete:

- During the turn initiation (①), the ski is flat (roll = 0°).
- The steering phase of the turn (②) lasts until the ski's orientation reaches the fall line (heading = 0°). During this phase, the roll (edging) angle increases gradually and reaches its maximum (approximately 50°).

The skidding of the skis can be obtained by analyzing its orientation with respect to its velocity vector. In this example, this angle is zero at the initiation (①) and increases during the first phase of the curve (②, Figure 5). To study the carving and slipping phases of a turn, it is interesting to display the skidding angles with respect to the trajectory (Figure 6).

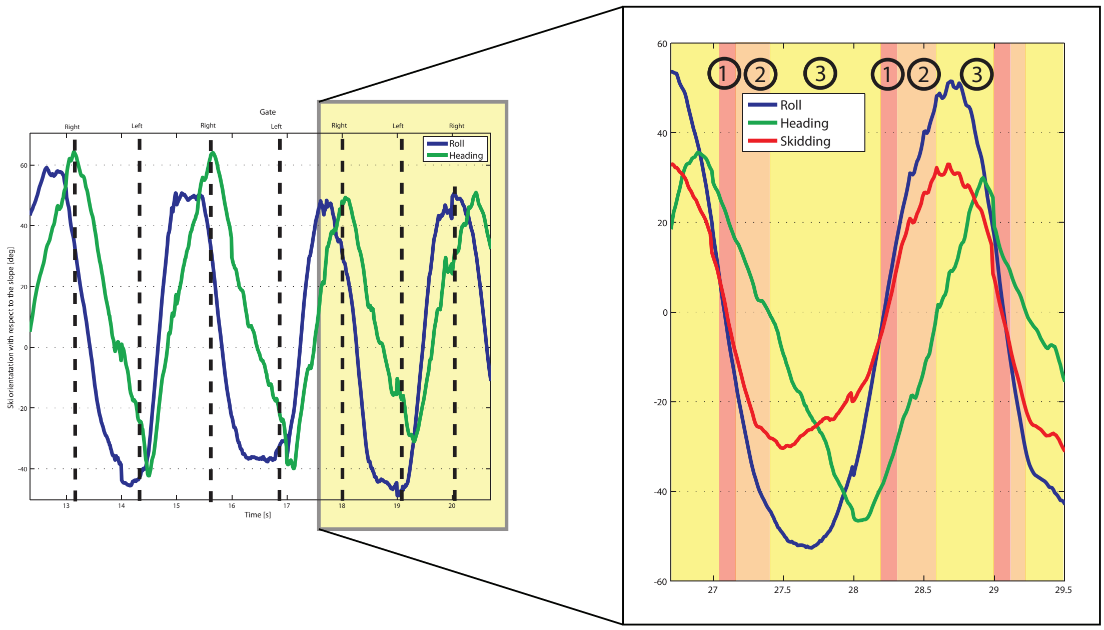


**Figure 5: Illustration of the roll (edging), heading and skidding angles during two turns.**

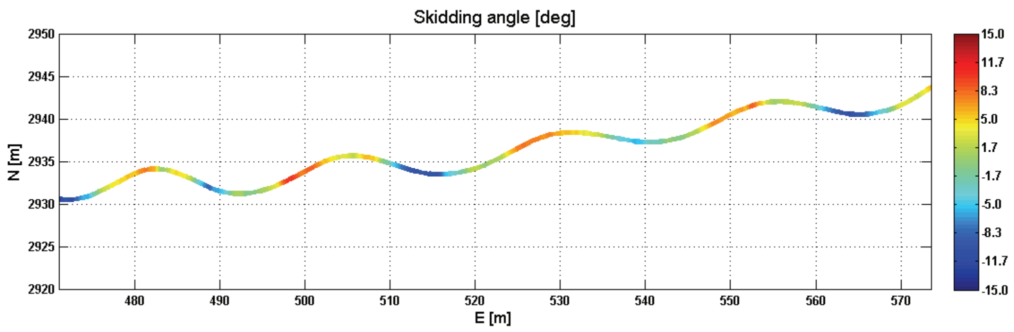


**Figure 6: Illustration of the skidding angle on the trajectory.**

**GPS Timing Accuracy Assessment**

On the contrary to traditional discrete character of chronometry with timing cells, the timing based on GPS (or GPS/MEMS-IMU) trajectories is continuous along the whole trajectory. This fact certainly has many advantages: The comparisons can be made over smaller sections (for example between two gates) and it can include topological aspects such as finding an ideal line by comparing different tracks. Furthermore, other parameters related to a defined section of the track (heart rate, velocity etc.) can be compared (Waegli and Skaloud 2007). In this section, we investigate the timing accuracy based on positioning.

The theoretical accuracy of timing derived from trajectories can be deduced from the following basic relation:

$$\Delta x = \frac{v}{\Delta t} \qquad \textbf{Equation 1}$$

Hence, considering a speed ( $v$ ) of 80km/h and a large (differential) positioning error ( $\Delta x$ ) of 0.4m leads to a timing error ( $\Delta t$ ) of 1.8/100s.

To verify this assumption, we set up an experiment where GPS synchronized timing cells (DATA Sports FRIWO) were placed along the trajectory. The positions of the gates were determined by static GPS sessions with an accuracy of 2-5cm. As the GPS antenna was placed on the athlete's helmet while the timing cells were actuated by the feet, the virtual timing based on the GPS trajectory had to be corrected for this difference (ΔT). Knowing that GPS time is stable at the nano-second level, it was then possible to compare accurately the splits of the timing cells with that based on the trajectory.


**Figure 7: Timing cells versus virtual timing derived from GPS.**

After evaluation of 7 runs, an average timing difference ($\Delta t$) of 2.2/100s was found. This value corresponds to the theoretical model and reflects the positioning accuracy. While timing cells provide only discrete measurements, trajectory-based timing provides a flexible approach which is independent of the skiers' posture. This result also confirms the findings of (Waegli and Skaloud 2007) where two pairs of skis were compared based on timing derived from GPS and traditional chronometry. There, the timing accuracies achieved with both methods were equivalent.

## DISCUSSION

Economical reasons and ergonomic constraints require the employment of small, low-cost L1 GPS receivers and inertial sensors of MEMS-type. The use of dual-frequency GPS receivers would increase the positioning accuracy to the decimeter level while the velocity and orientation accuracy would remain almost unaffected. However, the current pricing of dual-frequency GPS receivers restricts their use to a few athletes and applications with high accuracy requirements. To improve the orientation accuracy, higher-order IMU would have to be employed which reduces the portability and increases the cost of the system. An alternative consists in using redundant inertial system, a method which is currently investigated.

Trajectory and timing derived from GPS/MEMS-IMU present an interesting alternative to traditional methods applied for material testing and athletes' performance analysis. The presented low-cost system offers additional flexibility through continuous and accurate observation of an athlete's trajectory, including timing, position, velocity, acceleration and orientation. It has been shown that sufficient accuracy can be obtained even with low-cost sensors and that MEMS-IMUs are able to bridge lack of GPS data efficiently. We also illustrated in an example how these data can be further analyzed to retrieve additional knowledge. For instance by comparing the skis' trajectory with the skis' orientation, the skis' skidding angle can be derived.

Integrating the information obtained from digital terrain models allows determining the heading and edging of the skis.

## ACKNOWLEDGEMENT

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## REFERENCES

Richards, J. G. (1999). "The measurement of human motion: A comparison of commercially available systems." Human Movement Science **18**: 589-602.

Skaloud, J., J. Vallet, et al. (2006). "An Eye for Landscapes - Rapid Aerial Mapping with Handheld Sensors." GPS World **May 2006**(17 (5)): 26-32.

Titterton, D. H. and J. L. Weston (1997). Strapdown inertial navigation technology, Peter Peregrinus Ltd.

Waegli, A. and J. Skaloud (2007). Assessment of GPS/MEMS-IMU Integration Performance in Ski Racing. ENC, Geneva, Switzerland.

Waegli, A. and J. Skaloud (2007). "Turning Point – Trajectory Analysis for Skiers." InsideGNSS(Spring 2007).

Waegli, A., J. Skaloud, et al. (2007). Assessment of the Integration Strategy between GPS and Body-Worn MEMS Sensors with Application to Sports. ION GNSS, Fort Worth, Texas.